Paleoseismology

The following exercise is taken from:


PURPOSE

Paleoseismology is the study of earthquakes in the recent geologic past. In particular, the focus of research is on the occurrence, size, and timing of prehistoric earthquakes. The history of past earthquakes is the best tool for predicting the location, size, and frequency of future earthquakes. Past earthquakes are recorded best where faulting coincides with active deposition. Fault trenching is a method for exposing faulted sediments and deciphering the history of earthquake activity. The purpose of this exercise is to familiarize you with the technique of fault trenching, illustrate stratigraphic evidence of earthquakes, and show you how to interpret that evidence.

INTRODUCTION

The principle challenge in many fields of geology is seeing the features to be studied. Field geologists scour an area for useful outcrops and interpolate their data between these fixed points; petroleum geologists drill kilometers through sedimentary rock to infer the stratigraphic and structural relationships beneath the surface; and seismologists use seismic waves to interpret the composition of the Earth’s core and mantle. Geologists who study active faults are at the same disadvantage – earthquakes that occur today may rupture the surface, but erosion quickly erases that evidence in many settings. The history of past earthquakes is the key to predicting future earthquakes, but that history often lies buried beneath the surface.

Fault trenching is a technique developed in the last couple of decades to reveal evidence of past earthquakes in near-surface sediments. The principle is that if the fault won’t come up to the geologist, the geologist will go down to the fault. Using a bulldozer, backhoe, or pick and shovel, one or more long ditches are cut across a fault that is active or suspected to be active. A scientific fault trench is not just a hole in the ground, but should have the following features:
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- the trench should cross a fault or suspected fault
- one or more of the trench walls should be vertical
- the trench should cut sediments that accumulated during the period of fault activity
- the sediments should contain material suitable for radiocarbon or other numerical dating techniques.

Trench walls are vertical because only vertical walls clearly display the detailed stratigraphic layers and fault structures that need to be studied. The most successfully trenches reveal a detailed stratigraphy that accumulated during the same time interval that the fault was active. A Cambrian sedimentary rock that accumulated between 610 and 600 million years ago, for example, would provide little information about a fault active in the last few thousand years. Ideally, the stratigraphy in a fault trench consists of fine layers rich in organic material, so that the ages of earthquake events on that fault can be tightly bracketed by numerical ages.

Determining the ages of earthquake events revealed in a fault trench relies upon the two most basic axioms of stratigraphy: the principle of superposition and the principle of cross-cutting relationships. The principle of superposition states that sedimentary layers accumulate from the bottom up, so that any layer is younger than the layers beneath it and older than the layers above (Figure 9.1A). The principle of cross-cutting relationships states that if geological feature #1 cuts geological feature #2, then feature #2 is older than feature #1. In Figure 9.1B below, fault Y cuts layer C. We therefore know that layer C was deposited before Y last ruptured.

![Figure 9.1](image)

The location of a fault trench or a series of trenches is crucial to the success of the investigation. Most importantly, the location of the fault should be determined with fair precision before any excavation begins. The geologist almost certainly does not own the land he or she is tearing up, and disruption of the surface should be as little as possible to accomplish the scientific goals. In addition, excavating equipment often costs $100 per hour or more, so good planning is essential. When a geologist digs part of a trench by hand, the punishment for poor planning is lost days, sore muscles, blistered hands, and untold frustration.
One of the groundbreaking studies (so to speak) that utilized fault trenching was an investigation of the San Andreas fault at Pallett Creek, about 55 km (35 mi) northeast of Los Angeles, California (Sieh, 1978; Sieh, 1984). The segment of the San Andreas ruptured last in 1857 in an earthquake that was at least $M_w=7.8-7.9$, with slip on the fault between 3 and 4.5 m (10-15 ft). The age and displacement of the 1857 earthquake was known, but geologists had no history of previous earthquakes from which to calculate future earthquake hazard. Pallett Creek was a promising site because the area was swampland until the early 1900s, after which the creek began incising, cutting a 10 m deep canyon and lowering the groundwater table in the surrounding sediments. Figure 9.2 shows the series of trench cuts made on the north side of Pallett Creek to expose sediments cut by the San Andreas fault. The different exposures were cut using a backhoe (Exposures 10, 10a, 11, 11a, and 11b), a bulldozer (Exposure 5), and by hand (Exposures 1, 2, 3, 5, and 7).

Figure 9.2. Excavations across the San Andreas fault at Pallett Creek, about 55 km northeast of Los Angeles.
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INTERPRETING EARTHQUAKE EVENTS IN A TRENCH EXPOSURE

Earthquake events can be recorded in a stratigraphic sequence by a number of different features. The clearest evidence of fault rupture is displaced strata (Figure 9.3A). Where strata are continuous over distances of a few meters or more, distinct fault breaks may be recognized. The highest layer that is broken by a given fault strand gives the maximum age of that earthquake event; the lowest layer that is not broken gives the minimum age. Note that the amount of offset on pure normal and reverse faults can be measured directly from displaced strata, but displacement does not give the offset on strike-slip or oblique faults.

Where a fault ruptures in or near wet and unconsolidated sediments, sand boils often form (Figure 9.3B). These features, also called “sand craters” or “sand volcanoes,” form when seismic shaking liquefies sediment beneath the surface. Sand is less dense than silt and clay, so that liquefied sand is forced to the surface by the weight of the overlying material. After the 1811-12 earthquake sequence near New Madrid, Missouri (see Regional Focus D), numerous sand boils were found on the surface in the epicentral area. In cross section, a sand boil consists of a vertical feeder pipe connected to a filled crater and a sheet of sand or silt that covered the surface at the time of the earthquake.

Intense seismic shaking also can crack the surface, both near a fault and some distance away. Continued deposition of sediment fills these cracks. In a stratigraphic sequence near an active fault, these filled fissures (Figure 9.3C) can indicate an earthquake event if several of them occur at the same horizon.

The fourth stratigraphic feature that may indicate ancient earthquakes is a colluvial wedge (Figure 9.3D). Colluvium is sediment deposited by gravity. When a fault scarp forms in unconsolidated sediment, it often is steeper than the angle of repose of that material. Gravity carried the excess sediment down the slope, forming a wedge-shaped mass of colluvium at the base of the scarp. Continued deposition at the site buries the colluvial wedge. In a trench, colluvial wedges can be recognized by their shape, poor sorting of the material, and by intimate association with a fault plane.

![Figure 9.3. Stratigraphic evidence of earthquakes.](image)

**A**

**B**

**C**

**D**
Figure 9.4. Stratigraphic column at Pallett Creek trench site. (From Sieh et al, 1989).
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Figure 9.4 on the previous page is a generalized description of the stratigraphy at Pallet Creek, including the results of radiocarbon dates from several of the different layers. The ages of layers without radiocarbon dates can be bracketed using the principle of superposition. For example, layer 55 must have been deposited after 1050 A.D. but before 1100 A.D. You will use these dates to determine the ages of some of the earthquake events on the San Andreas fault at this site. The principle of cross-cutting relationships is the most useful tool for determining the age of an earthquake. For example, if layer 59 is displaced by a fault rupture but layer 61 is not cut, then that rupture must have occurred after 1100 A.D. but before 1335 A.D.

Figure 9.5. Exposure 7 at Pallet Creek.

The figure above (Figure 9.5) illustrates at least two different earthquake events. Locate the area labeled F-7-1 in Figure 9.5.

1) What kind of feature is F-7-1?

2) Assume that the numbers on the left side of Figure 9.4 are numerical ages that you can use to bracket different strata as well as earthquake events. For example, stratigraphic unit 13 formed between 150 and 400 A.D. What are the maximum and minimum ages that bracket the earthquake that formed F-7-1?

3) Enter that age information into Table 9.1 on the next page for Earthquake Event F.
4) Examine Figure 9.6. Determine the maximum and minimum ages for Earthquake Events N and T. Enter this information in Table 9.1.

5) Complete Table 9.1. To estimate the actual date of each earthquake event, you will average the maximum and minimum estimates. For example, Earthquake Event X occurred some time between 1753 and 1817 A.D. Using this method, you'll estimate that the earthquake occurred around 1785 A.D. In addition, you will estimate the recurrence interval between each pair of earthquakes. For example the interval between Event X (1785 A.D.) and Event Z (1857 A.D.) is 72 years.

6) Estimate the average recurrence interval for earthquakes on this segment of the San Andreas fault by averaging the times between all of the earthquakes recorded at Pallet Creek. Enter this estimate at the bottom of Table 9.1.

Table 9.1. Earthquake events at Pallet Creek. (Dates from Sieh et al, 1989)

<table>
<thead>
<tr>
<th>Earthquake Event</th>
<th>Overlying unit</th>
<th>min. age (A.D.)</th>
<th>average age estimate (min.+ max.+2)</th>
<th>Recurrence Interval (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>93</td>
<td>88</td>
<td>Jan. 9, 1857</td>
<td>72</td>
</tr>
<tr>
<td>X</td>
<td>88</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>71</td>
<td>1455</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>1465</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>61</td>
<td>1165</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
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<td></td>
<td></td>
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<tr>
<td>I</td>
<td>47</td>
<td>1013</td>
<td></td>
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</tr>
<tr>
<td>N</td>
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<tr>
<td>F</td>
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<tr>
<td>D</td>
<td>35</td>
<td>747</td>
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<tr>
<td></td>
<td>34</td>
<td>721</td>
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<td></td>
<td>20</td>
<td>400</td>
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<tr>
<td></td>
<td>18</td>
<td>210</td>
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</table>

Average Recurrence Interval =
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7. Plot the ages of all of the earthquakes in Table 9.1 in the graph below. Because each age is merely an estimated range, you will need to draw each earthquake as a horizontal bar. Earthquake Event B is plotted for you as an example.

8) Can you connect all or most of the earthquakes in the graph above with a straight line? The *characteristic earthquake* model says that the same faults are characterized by earthquakes with roughly the same magnitude that occur at roughly equal time intervals. How well does this model seem to work for this segment of the San Andreas fault?

An additional piece of evidence that you have is that the San Andreas fault system moves at an average rate of about 3.2 cm/year. Figure 9.7 on the next page shows the interrelationship between recurrence interval, long-term slip rate, and characteristic earthquake magnitude. Knowing any two of these parameters for a given fault system, you can estimate the third. For example, a fault that slips at an average rate of 1 mm/yr and has an earthquake recurrence interval of 1000 years is characterized by earthquakes with magnitudes around 7.0.
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![Graph showing the relationship between earthquake magnitude and average recurrence interval](image)

Figure 9.7. General relationship between recurrence interval, long-term slip rate, and characteristic earthquake magnitude. Earthquake magnitude (horizontal axis) is found by plotting the intersection of recurrence interval (vertical axis) and slip rate (diagonal lines). (After Slemmons and DePolo, 1986)

9) Using the long-term slip rate of the San Andreas fault, your estimate of the average recurrence interval at Pallett Creek, and Figure 9.7, what is the characteristic earthquake magnitude for earthquakes along this segment of the fault?
BIBLIOGRAPHY


Acknowledgements: Much of the original data in this exercise and several of the figures come from Sieh (1984) and Sieh (1978). The author would like to thank Dr. Sieh for his permission to use this material.